The Use of Neural Networks to Enhance Sensorless Position Detection in Switched Reluctance Motors

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Abstract

This paper describes a novel method of sensorless position detection for a switched reluctance motor (SRM). The approach requires no special converter or sensor circuitry, and does not rely on accurate prior knowledge of the magnetic characteristics of the motor. The technique is based on the use of the main converters to inject short, fixed duration, diagnostic current pulses simultaneously into two unenergised phases of a four-phase SRM. Previously, such a technique has been used to estimate the inductance of the motor phase windings and, using stored knowledge of the relationship between inductance L , rotor position θ , and current i , to estimate rotor position. The approach described in this paper is novel in two respects. Firstly, it does not rely on prior knowledge of the function $L(\theta)$ but merely makes the assumption that L varies substantially as $\sin(N_r\theta)$, where N_r is the number of rotor poles. Secondly, the approach learns from good estimates of position and, once it has done this, is able to use this knowledge where performance of the estimation algorithm degrades (principally at low speeds of rotation).

1 Introduction

Due to the simplicity of its construction, the switched reluctance motor (SRM) has potential advantages over other types of electrical drive in both cost and reliability. However, in order to control a switched reluctance motor effectively, it is necessary to synchronise the excitation of its phase windings with rotor position and this implies the need either to sense or to estimate its rotor position. Optical or electromagnetic sensors add to the cost, complexity and potential unreliability of SRM drives and this has motivated the investigation of sensorless position estimation by a number of researchers, e.g. [1]-[4]. Ray and Al-Bahadly [5] review a number of different approaches.

The fundamental characteristic of a switched reluctance motor exploited by impedance sensing methods of position estimation is the variation in inductance of its phase windings with rotor angle, θ and phase winding current, i. The exact nature of the function $L(\theta, i)$ is a function of the geometry of the motor and is not easily predicted. A technique for sensorless position estimation in switched reluctance motors based on probing unenergised phase windings using short voltage pulses from the main converter and which does not rely on *a priori* knowledge of the inductance characteristic is described in this paper.

2 Impedance Sensing Based Position Estimation

One method [2, 3, 4] of estimating rotor position is to apply voltage pulses of short duration to an unenergised, phase and estimate the inductance of that phase from measured changes in the resulting current. The current flowing in a phase winding is described by

$$v = Ri + L(\theta, i)\frac{di}{dt} + i\frac{dL(\theta, i)}{dt} \qquad (1)$$

where v is the voltage across the phase, i is the phase current and R and $L(\theta, i)$ are the resistance and inductance of the phase. If a probing voltage, V is applied for a short time, Δt then i will be small, θ may be regarded as constant, L will not saturate and (1) may be approximated by

$$V = L(\theta)\frac{\Delta i}{\Delta t} \qquad (2)$$

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where Δi is the change in phase current over time Δt. Phase inductance may then be estimated using

$$\hat{L} = V\frac{\Delta t}{\Delta i} \tag{3}$$

If V and Δt are held constant in (2) then the measured change in current, Δi can yield absolute rotor position information, provided that the function

$$\hat{\theta} = G^{-1}(\hat{L}) \tag{4}$$

where

$$L = G(\theta) \tag{5}$$

is already known. Typically, Δi is digitised using an analogue to digital converter and the estimation algorithm implemented on a microprocessor [3, 4, 6] The small values of i involved in this technique exert only a small negative torque on the rotor.

2.1 Proposed Technique

In a four-phase SRM, two quadrature unenergised phases are always available to be probed as described above, yielding inductance estimates

$$\begin{aligned}\hat{L}_a &= V\frac{\Delta t}{\Delta i_a}\\ \hat{L}_b &= V\frac{\Delta t}{\Delta i_b}\end{aligned} \tag{6}$$

Assuming [2, ?] that

$$L_a = L_{mid} + L_{mag}cos(N_r\theta) \tag{7}$$

and

$$L_b = L_{mid} - L_{mag}sin(N_r\theta) \tag{8}$$

where

$$\begin{aligned}L_{mid} &= \frac{L_{max} + L_{min}}{2}\\ L_{mid} &= \frac{L_{max} - L_{min}}{2}\end{aligned} \tag{9}$$

differentiating (7) and (8) each with respect to θ and dividing one result by the other yields

$$\frac{dL_a}{dL_b} = \tan(N_r\theta) \tag{10}$$

and hence

$$\theta = \frac{1}{N_r}\tan^{-1}\left(\frac{dL_a}{dL_b}\right) \tag{11}$$

Estimating dL_a and dL_b by

$$\begin{aligned}\Delta\hat{L}_a &= \hat{L}_a(k) - \hat{L}_a(k-1)\\ \Delta\hat{L}_b &= \hat{L}_b(k) - \hat{L}_b(k-1)\end{aligned} \tag{12}$$

where $\hat{L}_a(k)$ represents the estimate of L_a at time $t = k\Delta t$, an estimate of rotor position

$$\begin{aligned}\hat{\theta} &= \frac{1}{N_r}\tan^{-1}\left(\frac{\Delta\hat{L}_a}{\Delta\hat{L}_b}\right)\\ &= \frac{1}{N_r}\tan^{-1}\left(\frac{\frac{1}{\Delta i_a(k)} - \frac{1}{\Delta i_a(k-1)}}{\frac{1}{\Delta i_b(k)} - \frac{1}{\Delta i_b(k-1)}}\right)\end{aligned} \tag{13}$$

may be made.

Figure 1 shows experimental measurements, made at low current levels, of the inductance of one of the four phases of a switched reluctance motor. These appear to validate the assumptions of (7) and (8). A

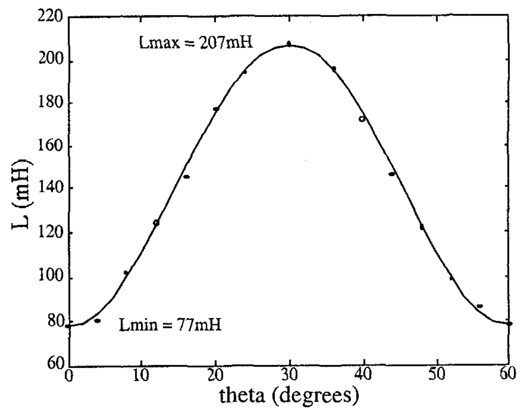

Figure 1: Phase inductance vs. rotor position in a four-phase SRM

strength of the method proposed is that it does not rely on the absolute values of the inductance estimates or on the use of a pre-stored characteristic, but yields absolute position $\hat{\theta}$ information directly. Additionally, the technique is independent of applied voltage V.

2.2 Limitations of the Proposed Technique

The impedance sensing techniques described above cannot be used at rotor speeds above that at which a probing pulse will occupy more than half of a phase period [6]. The proposed technique is, in addition, limited at low speeds. As described by Harris [4], quantisation of the current measurements is an important feature affecting the accuracy of inductance estimates. In the proposed technique, quantisation is even more important. If successive current measurements differ by less than one quantisation level, as will be the case at low speed, then estimates of ΔL will be equal to zero and equation (13) will yield no useful information. In other words, (13) is effective only over a limited range of rotor speeds.

2.3 Enhancement of the Proposed Technique

The proposed solution to the low speed problem is to predict the effectiveness of the estimation technique on a sample by sample basis and, if necessary, to estimate rotor position by another method. The alternative method proposed is to recall $\hat{\theta}$ as a function of Δi_a and Δi_b using a neural network that has been trained during satisfactory operation of the estimator. The scheme is illustrated in figure 2.

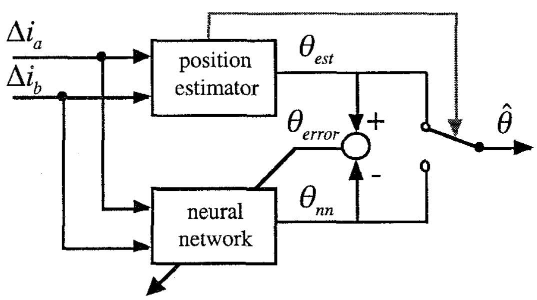

Figure 2: block diagram

If the magnitude of the difference between successive samples of either Δi_a or Δi_b is less than a threshold value then θ is estimated as a function of Δi_a and Δi_b using the neural network. Otherwise, θ is estimated using equation (13) and the neural network is trained using Δi_a and Δi_b as inputs and $\theta_{error} = \theta_{est} - \theta_{nn}$ as an error signal.

2.4 CMAC Neural Network

The cerebellar model articulation controller (CMAC) neural network [7]is well suited to the application described here. Its characteristics include local generalisation, fast learning and temporal stability. CMAC networks are afflicted by the curse of dimensionality. However, the requirements of this application, i.e. two inputs, Δi_a and Δi_b, and one output, θ_{nn} are modest. CMAC neural networks are particularly amenable to implementation in digital hardware. An inexpensive, high speed, hardware implementation of a CMAC network of these dimensions has been demonstrated previously [8].

3 Simulation Results

Several aspects of the proposed technique have been investigated in simulation. In particular, the performance of the technique at low rotor speeds and the use of different resolutions of analogue to digital converter to measure Δi_a and Δi_b have been investigated. It was assumed in the simulation that the phase inductances L_a and L_b varied sinusoidally with θ. For clarity, the simulations considered constant speed operation of the motor. The values $L_{max} = 207$ mH and $L_{min} = 77$ mH shown in figure 1 were used and the the probing frequency was fixed at 10kHz. Figure 3 shows esti-

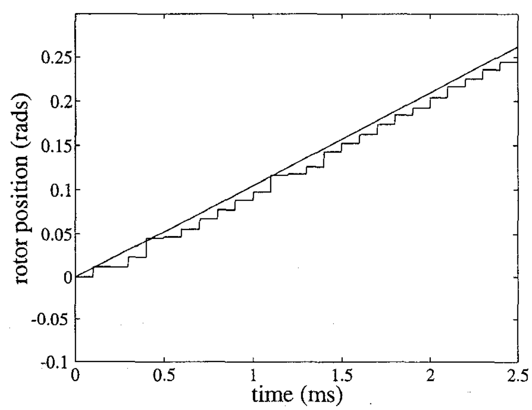

Figure 3: Estimated and actual rotor position at $\omega = 1000$ r/min using proposed technique

mated and actual rotor positions vs. time, using the impedance sensing technique proposed in section 2.1 at a rotor speed of $\omega = 1000$ r/min and using a 10-bit

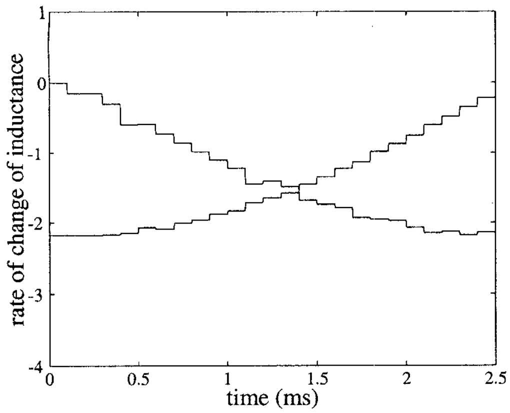

Figure 4: Estimated rates of change of inductance, $\Delta\hat{L}_a$ and $\Delta\hat{L}_b$, at $\omega = 1000$ r/min

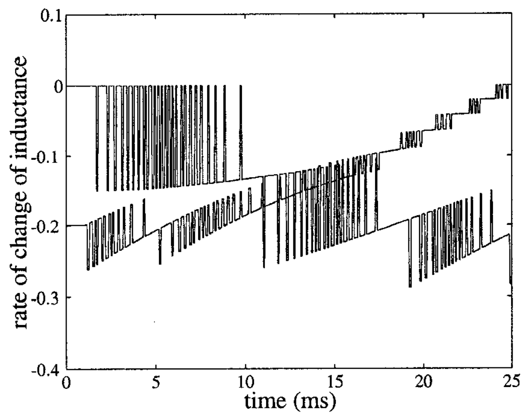

Figure 6: Estimated rates of change of inductance, $\Delta\hat{L}_a$ and $\Delta\hat{L}_b$, at $\omega = 100$ r/min

analogue to digital converter. The corresponding estimated rates of change of inductance, $\Delta\hat{L}_a$ and $\Delta\hat{L}_b$ are shown in figure 4. At a rotor speed of $\omega = 1000$ r/min, the estimator is considered to be effective. Figures 5 and 6 correspond to figures 3 and 4 but at a rotor speed of $\omega = 100$ r/min. In this case, the performance of the estimator has degraded markedly. The reason for this can be seen in figure 6 where the value of $\Delta\hat{L}_a$ is zero for much of the first 10 ms shown. A zero value of $\Delta\hat{L}_a$ corresponds to no difference between the quantised values of two consecutive current measurements.

Effective performance of the estimator can, in theory, be extended to lower rotor speeds by increasing the resolution of the analogue to digital converter used to quantise current measurements. Figure 7 shows estimated and actual rotor positions vs. time at a speed of $\omega = 100$ r/min using a neural network to enhance the performance of the estimator. The simulation results shown in the figure were obtained following 200 ms of training of the neural network at rotor speeds between 500 and 1000 r/min, starting with no knowledge of the motor characteristics. Compared with figure 5, the position errors are significantly reduced.

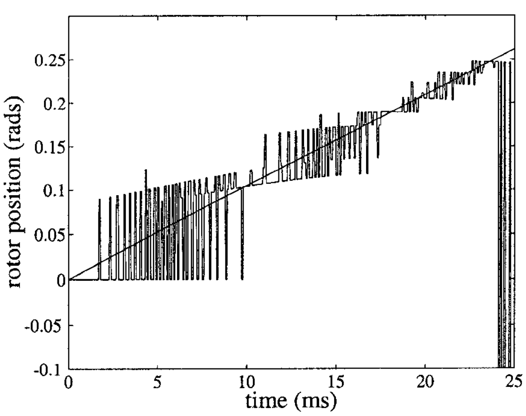

Figure 5: Estimated and actual rotor position at $\omega = 100$ r/min using proposed technique

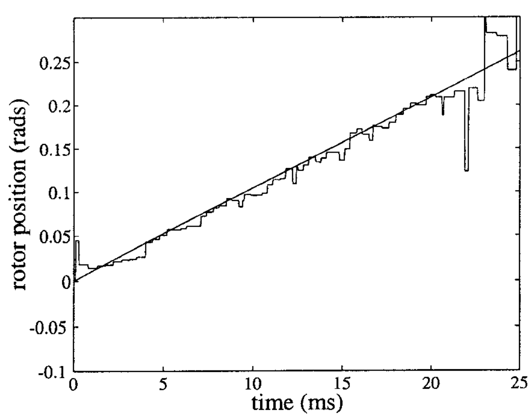

Figure 7: Estimated and actual rotor position at $\omega = 100$ r/min using neural network enhanced technique

4 Discussion

Two features of the technique are of particular interest. Firstly, it relies on the basic position estimation technique having run sufficiently effectively for the neural network to have learned the relationship between Δi_a, Δi_b and $\hat{\theta}$. CMAC networks learn quickly and, assuming that a motor *can* be run at speeds at which the estimator is effective, there should be no shortage of training data. A neural network would be able to recall the function learned in previous use of a motor or might be pre-loaded with an initial estimate of the relationship between Δi_a, Δi_b and $\hat{\theta}$. In contrast to the position estimator, the function learned by the neural network is dependent on the probing voltage, V. Secondly, the technique relies on an assumption that the function $L(\theta)$ is sinusoidal. Experimental measurements of the phase inductance appear to validate this assumption for the motor used in this work, but further work will investigate the extent of errors introduced as this assumption becomes less valid.

5 Conclusions

A novel technique for sensorless rotor position detection has been described. Its operation over a range of speeds has been discussed and, in particular, its performance at low speeds analysed. An enhancement that extends its performance to lower rotor speeds has been proposed. The proposed technique makes use of a neural network in order to learn position as a function of the currents resulting from the probing of unenergised phase windings. The advantages of the proposed technique are that it does not rely on accurate prior knowledge of the magnetic characteristics of a motor and is independent of the probing voltage, V. The effectiveness of the technique has been demonstrated in simulation.

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